Application of MCNP Code in Shielding Design for Radioactive Sources

Ibrahim A. Alrammah

***Abstract*—**This paper presents three tasks: Task 1 explores: the detected number of neutrons as a function of polythene moderator thickness; the influence of adding polythene moderator behind the detector ; the influence of borated polythene and cadmium absorbers on the observed neutron flux; and compares between experiment and simulation for the photon shielding experiment.

The objective of Task 2 is to perform calculations to determine the thickness of material required to reduce the intensity of the incident radiation of Cs-137 source by a factor of 2. The calculations consider three types of shielding: lead, copper and aluminum. The calculated values of the required thickness will be compared to the values resulted from experiment and simulation.

The goal of Task 3 is to extend the work that has been done and to develop an MCNP model that produces a 5 mm width collimated beam of thermal neutrons from a point isotropic Am/Be source of neutrons.

***Keywords*—Radiation Shielding, MCNP, Polythene, Cadmium.**

I. Introduction

Radioactive materials are used in numerous areas such as medicine, research, industry and nuclear power production. MCNP is a general-purpose Monte Carlo N-Particle code that can be utilized for neutron, photon, electron, or coupled neutron/photon/electron transport. Specific fields of application comprise but are not limited to: radiation protection and dosimetry, radiography, radiation shielding, nuclear criticality safety, medical physics, nuclear oil well logging, detector design and analysis, fission and fusion reactor design, accelerator target design, decontamination and decommissioning. MCNP code treats a random three-dimensional configuration of materials in geometric cells bounded by first- and second-degree surfaces and fourth-degree elliptical tori.

This work presents three tasks: Task 1 studies and explores: the detected number of neutrons as a function of polythene moderator thickness; the influence of adding polythene moderator behind the detector ; the influence of borated polythene and cadmium absorbers on the observed neutron flux; and compares between experiment and simulation for the photon shielding experiment.

The objective of Task 2 is to perform calculations to determine the thickness of material required to reduce the intensity of the incident radiation of Cs-137 source by a factor of 2. The calculations consider three types of shielding: lead, copper and aluminum. The calculated values of the required thickness will be compared to the values resulted from experiment and simulation.

The objective of Task 3 is to extend the work that has been done and to develop an MCNP model that produces a 5 mm width collimated beam of thermal neutrons from a point isotropic Am/Be source of neutrons.

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II. Task 1

A. The detected number of neutrons as a function of polythene moderator thickness:

The effect of varying the thickness of the polythene moderator was studied. TABLE 1 summarizes the MCNP simulation outputs of scenario A.1 (polythene moderator between source and detector).

TABLE I
MCNP simulation outputs of scenario A.1

Thickness (mm)	Tally 14 (incident neutrons)	Tally 24 (detected neutrons)	Ratio relative to zero moderator
0	1.18E-06	6.50E-08	1
2	7.21E-07	9.57E-09	1.47E-01
4	5.74E-07	1.29E-08	1.99E-01
6	4.78E-07	1.25E-08	1.93E-01
8	3.61E-07	1.10E-08	1.69E-01
10	2.96E-07	8.99E-09	1.38E-01
14	2.43E-07	7.66E-09	1.18E-01
16	1.69E-07	4.95E-09	7.62E-02

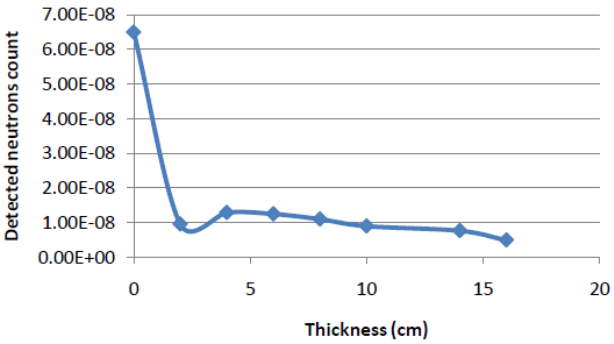

Fig. 1. Scenario A.1: Polythene moderator between source and unshielded detector.

Fig. 1 shows that increasing the thickness of the polythene moderator decreases the detected number of neutrons, as was expected.

The incident fast neutrons lose a fraction of their energy through the collisions with the hydrogen nuclei in the polythene sheet prior to reaching the detector, thus increasing the moderator thickness increases the number of collisions made by the neutron prior to reaching the detector; however, increasing the moderator thickness also decreases the detector volume-to-moderator volume ratio. A decrease in this ratio means the neutron has a lower probability of reaching the detector and thus a lower probability of being counted. Furthermore, a neutron may be absorbed within the thicker moderating material prior to reaching the detector.

Within the experimental uncertainties, the decrease in the neutron intensity agrees with Monte Carlo results. This study has provided an experimental base to verify Monte Carlo design calculations [1].

B. The influence of adding polythene moderator behind the detector

TABLE 2 summarizes the simulation outputs of scenario A.2 (polythene moderator on the far side of the detector**)**.

TABLE II
MCNP SIMULATION OUTPUTS OF SCENARIO A.2

Thickness (mm)	Tally 14 (incident neutrons)	Tally 24 (detected neutrons)	Ratio relative to zero moderator
0	1.03E-06	5.48E-08	1
2	1.06E-06	5.95E-08	1.09E+00
4	1.08E-06	6.14E-08	1.12E+00
6	1.08E-06	6.21E-08	1.13E+00
8	1.10E-06	6.30E-08	1.15E+00
10	1.09E-06	6.33E-08	1.15E+00
14	1.11E-06	6.50E-08	1.19E+00
16	1.12E-06	6.60E-08	1.20E+00

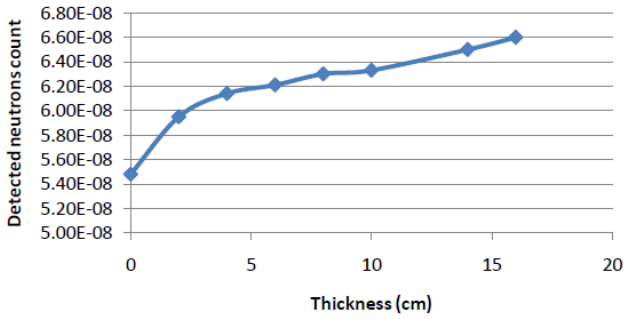

Fig. 2. Scenario A.2: Polythene moderator on the far side of the unshielded detector.

It shows an increase in the detected neutrons count with increasing the shield thickness. The fast neutrons from the source moderated by the polythene sheet, become thermal then reflected to be detected.

C. The influence of borated polythene and cadmium absorbers on the observed neutron flux:

TABLE 3 summarizes the simulation outputs of scenario B.1 (Borated Polythene Moderator between Source and Detector). Fig. 3 and 4 show decreasing in count rate with increasing the shield thickness, that means less thermal neutrons detected. Borated polythene has higher cross-section than polythene.

TABLE III
MCNP SIMULATION OUTPUTS OF SCENARIO B.1

Thickness (mm)	Tally 14 (incident neutrons)	Tally 24 (detected neutrons)	Ratio relative to zero moderator
0	1.18E-06	6.50E-08	1
2.5	6.20E-07	4.23E-09	5.27E-01
5	4.66E-07	3.54E-09	3.96E-01
7.5	3.46E-07	3.12E-09	2.94E-01
10	2.66E-07	2.25E-09	2.26E-01

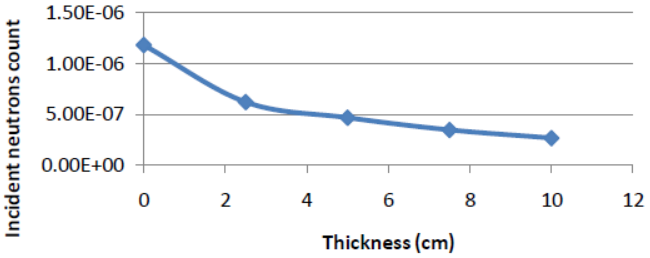

Fig. 3. Scenario B.1: Borated polythene moderator between source and detector.

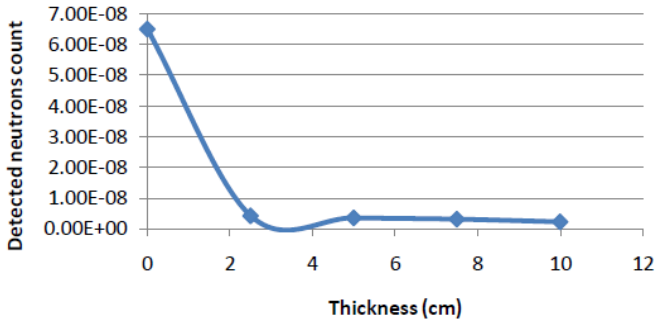

Fig. 4. Scenario B.1: Borated polythene moderator between source and detector.

Borated polythene contains high hydrogen content to provide good characteristics for the attenuation of fast neutrons. There appear to be competing effects of neutron moderation provided by carbon and hydrogen, and neutron capture provided by boron. TABLE 4 summarizes the simulation outputs of scenario C (Cadmium shielded detector).

TABLE IV
MCNP SIMULATION OUTPUTS OF SCENARIO C

Thickness (mm)	Tally 14 (incident neutrons)	Tally 24 (detected neutrons)	Ratio relative to zero moderator
0	8.71E-07	3.83E-09	1
2	6.81E-07	1.47E-09	3.84E-01
4	5.17E-07	1.26E-09	3.28E-01
6	4.19E-07	9.81E-10	2.56E-01
8	3.12E-07	9.25E-10	2.42E-01
10	2.54E-07	7.38E-10	1.93E-01
14	2.06E-07	6.26E-10	1.63E-01
16	1.45E-07	3.40E-10	8.89E-02

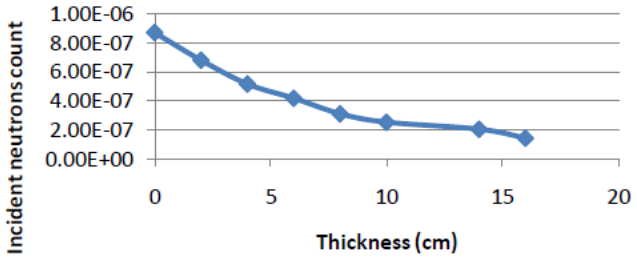

Fig. 5. Scenario C: Cadmium Shielded Detector.

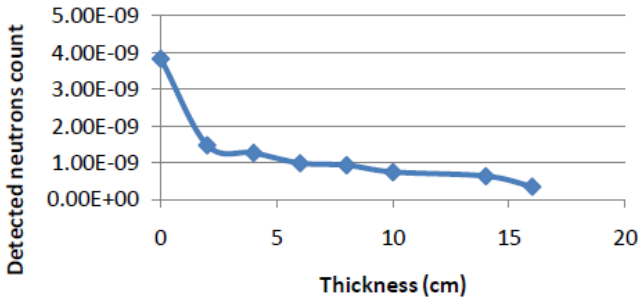

Fig. 6. Scenario C: Cadmium Shielded Detector.

Fig. 5 and show decreasing in counts with increasing the shield thickness, that means less thermal neutrons detected. Cadmium is a good neutrons absorber.

D. Comparison between experiment and simulation for the photon shielding experiment:

1) Lead Absorber:

TABLE 5 and Fig. 7 summarize the results from the experiment and MCNP simulation:

TABLE V
LEAD ABSORBER

Thickness (mm)	Experiment		MCNP	
	Count rate (Hz)	Ratio Relative to zero thickness absorber	Peak to total	Ratio Relative to zero thickness absorber
0	74	1	0.3058	1
2.6	54	0.7297	0.2825	0.9238
5.3	40	0.5405	0.2491	0.8145
7.9	29	0.3918	0.2486	0.8129

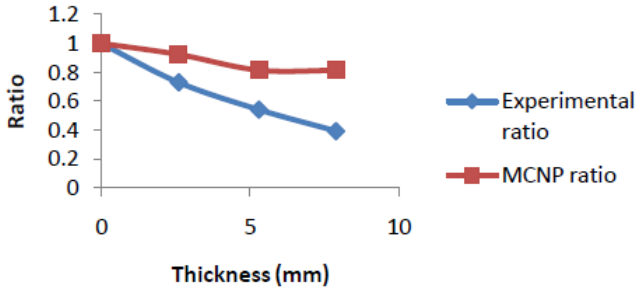

Fig. 7. Lead absorber.

2) Copper Absorber:

TABLE 6 and Fig. 8 summarize the results from the experiment and MCNP simulation:

TABLE VI
COPPER ABSORBER

Thickness (mm)	Experiment		MCNP	
	Count rate (Hz)	Ratio Relative to zero thickness absorber	Peak to total	Ratio Relative to zero thickness absorber
0	74	1	0.3058	1
6.6	48	0.648649	0.2351	0.768803
13.3	32	0.432432	0.1871	0.611838

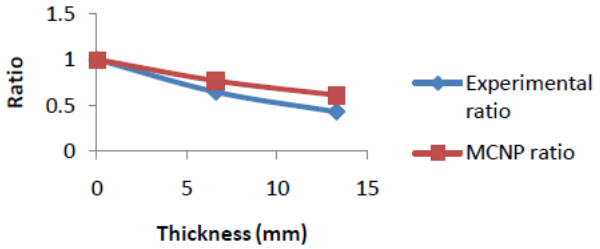

Fig. 8. Copper absorber.

3) Aluminum Absorber:

TABLE 7 and Fig. 9 summarize the results from the experiment and MCNP simulation:

TABLE VII
ALUMINUM ABSORBER

Thickness (mm)	Experiment		MCNP	
	Count rate (Hz)	Ratio Relative to zero thickness absorber	Peak to total	Ratio Relative to zero thickness absorber
0	74	1	0.3058	1
6.2	65	0.8784	0.2802	0.9163
12.3	57	0.7703	0.2587	0.8459
18.5	51	0.6892	0.237	0.7751
24.7	44	0.5946	0.2183	0.7139
30.8	40	0.5405	0.2016	0.6592
37	35	0.4729	0.1859	0.6079

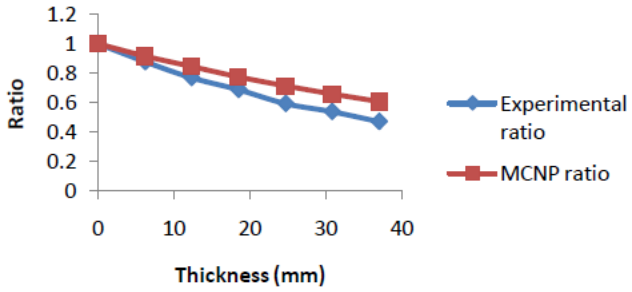

Fig. 9. Aluminum absorber.

E. Comments:

It is found that there is some agreement (to certain extent) between MCNP simulation and experiment. Both the experiment and the MCNP show decreasing trend of counts with increasing the thickness of absorber. However, it is found that the experiment requires narrower thickness of absorber than MCNP to achieve intensity reduction of the incident radiation by a factor of 2. This is true for the three materials under consideration: lead, copper and aluminum. That is, for lead

case, 7.9 mm thick absorber satisfied 39 % reduction of the incident radiation in the experiment. However, the same thickness satisfied 81 % reduction with MCNP. For copper case, 13.3 mm satisfied 43 % reduction in the experiment, while in MCNP, it satisfied 61 % reduction. For aluminum, 37 mm satisfied 47 % reduction in experiment, while in MCNP, it satisfied 61 % reduction. This might be due to several reasons. The following points are possible reasons:

- The noise present in the experiment from the surrounding objects that can act as an absorber, while it is not the case in the simulation.
- The materials characteristics (i.e. temperature, density, pressure, geometry, etc…) applied in the experiment may differ slightly from that of the simulation.
- In the experiment, multiple layers (sheets) of absorber were used. While in simulation they were considered as one layer.

Among the materials used in the experiment, it is found that the best gamma absorber is lead, which is followed by copper then aluminum. The good absorber materials can satisfy the required reduction in intensity with thinner thickness (7.9 mm of lead, 13.3 mm of copper, 37 mm of aluminum).

III. TASK 2: SHIELDING CALCULATIONS

The objective here is to perform some calculations to determine the thickness of material required to reduce the intensity of the incident radiation of Cs-137 source by a factor of 2. The calculations consider three types of shielding: lead, copper and aluminum. The calculated values of the required thickness will be compared to the values resulted from experiment and simulation.

These calculations are for a model of 2.9 cm radius and 7.5 long NaI detector surrounded by a shield of lead. A sheet of lead is carried by a base of aluminum which is placed in front of the detector. The source of radiation is placed 10 cm from the detector.

The attenuation coefficient provides an indication of how effective a given material is, per unit thickness, in promoting photon interactions. The larger the value of the attenuation coefficient, the more likely it is that photons of a given energy will interact in a given thickness of material. The attenuation coefficient is represented using the symbol μ, and measured in cm^{-1}. $I = I_o e^{-(\mu/\rho)x}$ Where:

I_o: is the intensity with no shielding.

ρ: is the thickness of shield material.

x: is the density of shield material.

The magnitude of the coefficient varies with material and with photon energy. The gamma-ray energy used in this experiment is 662 keV. From the Fig. 10-12, it can be stated the appropriate values of (μ/ρ) for: lead, copper and aluminum are: 1.25 cm^2/g, 0.6 cm^2/g and 0.20 cm^2/g, respectively.

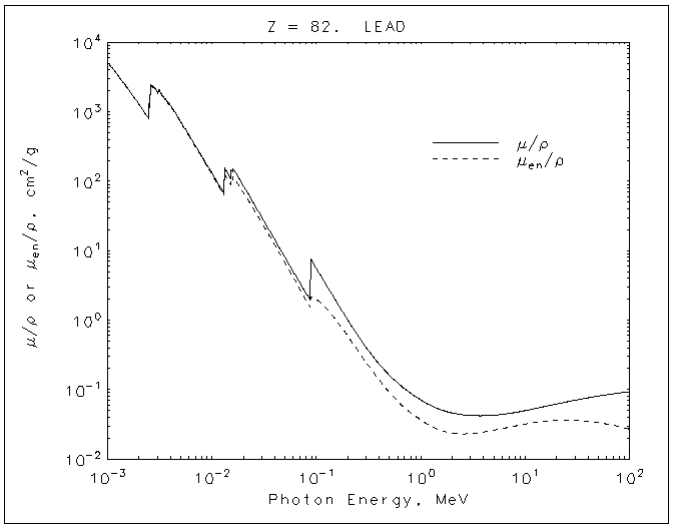

Fig. 10. Lead curve.

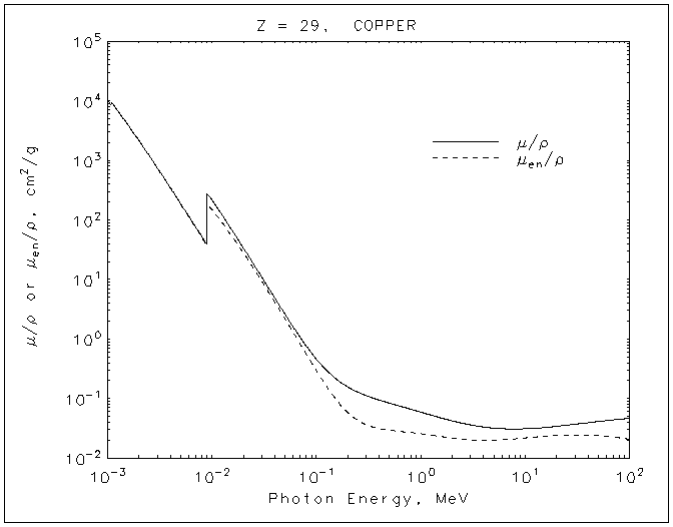

Fig. 11. Copper curve.

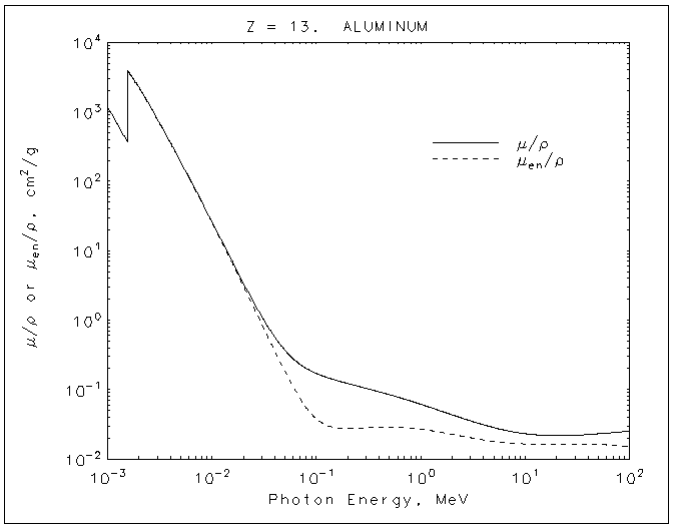

Fig. 12. Aluminum curve.

A. *Lead Shielding*

It is found in the experimental work that the count rate is 74 Hz when there is no shielding. This is to be reduced by factor of 2, i.e. 37 Hz. TABLE 8 summarizes the experimental results.

$$I/I_o = e^{-(\mu/\rho)x}$$
$$1/2 = e^{-(1.25)x}$$
$$x = \frac{\ln(2)}{1.25} = 0.555\ cm$$

TABLE VIII
LEAD SHIELDING

Thickness (mm)	Count rate (Hz)
0	74
2.6	54.2
5.3	39.6
7.9	29.2

By applying simple interpolation, the thickness *x* required according to the experiment can be found as:

$$\frac{7.9-5.3}{29.2-39.6} = \frac{7.9-x}{29.2-37}$$

x = 0.595 cm, with percent error of 7%.

B. *Copper Shielding*

$$1/2 = e^{-(0.6)x}$$
$$x = \frac{\ln(2)}{0.6} = 1.155\ cm$$

TABLE 9 summarizes the experimental results.

TABLE IX
COPPER SHIELDING

Thickness (mm)	Count rate (Hz)
0	74
6.6	48
13.3	32

By applying simple interpolation, the thickness *x* required according to the experiment can be found as: *x*= 1.12 cm with percent error of 3%.

C. *Aluminum Shielding*

$$1/2 = e^{-(0.2)x}$$
$$x = \frac{\ln(2)}{0.2} = 3.466\ cm$$

TABLE 10 summarizes the experimental results.

TABLE X
ALUMINUM SHIELDING

Thickness (mm)	Count rate (Hz)
0	74
6.2	65
12.3	57
18.5	51
24.7	44
30.8	40
37	35

By applying simple interpolation, the thickness *x* required according to the experiment can be found as: *x*= 3.450 cm with percent error of 0.5%, which means that there is good agreement, to certain extent, between the experimental and the theoretical results. It can be said that the two values agree.

A small linear attenuation coefficient indicates that the material in question is relatively transparent, while larger values indicate greater degrees of opacity [2].

IV. TASK 3: COLLIMATED BEAM OF THERMAL NEUTRONS

The objective here is to extend the work that has been done and to develop an MCNP model that produces a 5 mm width collimated beam of thermal neutrons from a point isotropic Am/Be source of neutrons.

The developed model constitutes of a point isotropic Am/Be source of neutrons located inside a tank of water. A fixed source-to-detector distance is used, and the count rate in the He-3 detector is recorded as polythene moderator is placed first, then a sheet of cadmium absorber is placed between the moderator and the detector. The cadmium sheet has a vertical slit of 5 mm width which produces a beam of thermal neutrons. The distance between the cadmium sheet and the detector has been varied to study the effect of beam divergence. The detector is segmented to 5 parts to show the number of incident and detected neutrons in each segment in order to illustrate the profile of beam incident on the He-3 detector. Fig. 13 illustrates this configuration.

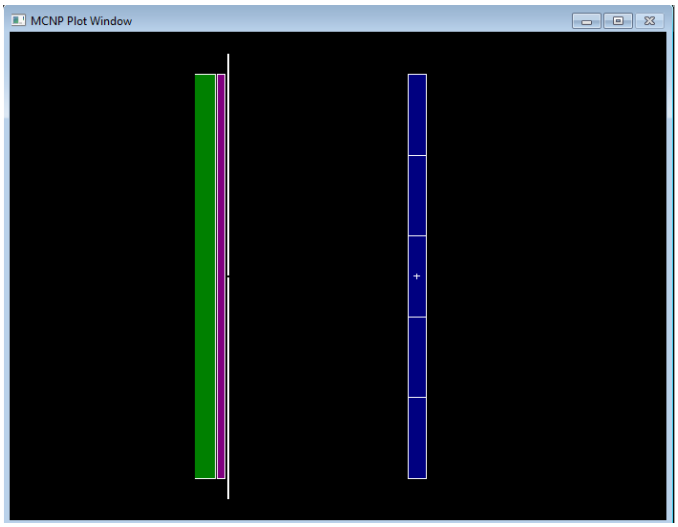

Fig. 13. MCNP configuration.

In this work, six scenarios were examined:

- Scenario A: with 47 cm distance between the collimated beam and the detector
- Scenario B: with 40 cm distance between the collimated beam and the detector
- Scenario C: with 30 cm distance between the collimated beam and the detector
- Scenario D: with 20 cm distance between the collimated beam and the detector
- Scenario E: with 10 cm distance between the collimated beam and the detector
- Scenario F: with 5 cm distance between the collimated beam and the detector.

TABLES 11-16 and Fig. 14-19 summarize the result of this simulation.

TABLE XI
SCENARIO A

Detector segment	Incident neutrons	Detected neutrons
1	4.74E-07	7.83E-10
2	7.76E-07	1.14E-09
3	8.60E-07	1.95E-09
4	8.05E-07	1.36E-09
5	4.41E-07	4.92E-10

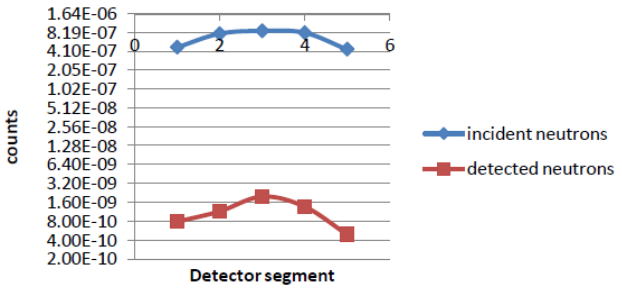

Fig. 14. Scenario A: 47 cm between collimator and detector

TABLE XII
SCENARIO B

Detector segment	Incident neutrons	Detected neutrons
1	4.69E-07	5.37E-10
2	7.59E-07	8.97E-10
3	8.72E-07	1.93E-09
4	7.91E-07	9.23E-10
5	4.46E-07	3.89E-10

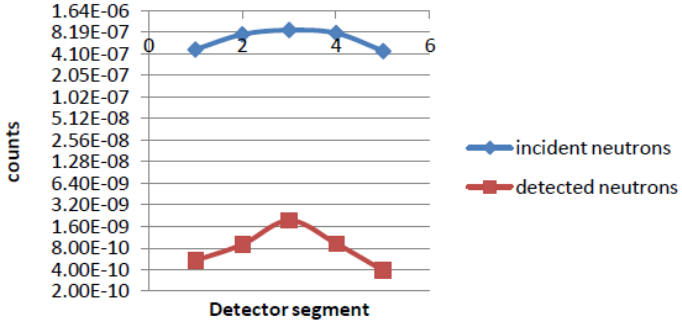

Fig. 15. Scenario B: 40 cm between collimator and detector

TABLE XIII
SCENARIO C

Detector segment	Incident neutrons	Detected neutrons
1	4.77E-07	6.35E-10
2	7.61E-07	9.95E-10
3	8.94E-07	2.33E-09
4	7.82E-07	9.04E-10
5	4.88E-07	4.29E-10

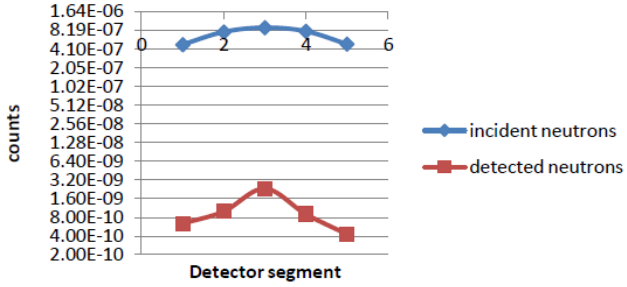

Fig. 16. Scenario C: 30 cm between collimator and detector

TABLE XIV
SCENARIO D

Detector segment	Incident neutrons	Detected neutrons
1	4.82E-07	5.65E-10
2	7.65E-07	7.06E-10
3	8.94E-07	1.93E-09
4	7.82E-07	5.50E-10
5	4.44E-07	3.90E-10

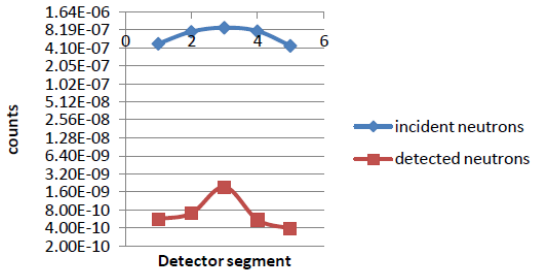

Fig. 17. Scenario D: 20 cm between collimator and detector

TABLE XV
SCENARIO E

Detector segment	Incident neutrons	Detected neutrons
1	4.87E-07	5.48E-10
2	7.61E-07	6.34E-10
3	8.89E-07	3.65E-09
4	8.18E-07	5.37E-10
5	4.51E-07	3.63E-10

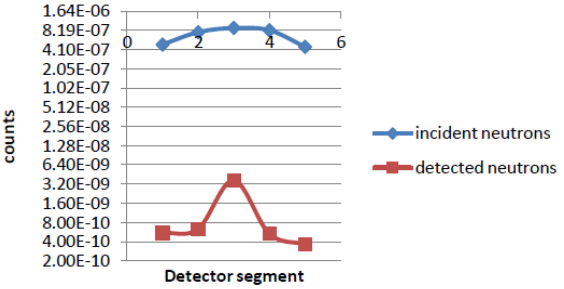

Fig. 18. Scenario E: 10 cm between collimator and detector

TABLE XVI
SCENARIO F

Detector segment	Incident neutrons	Detected neutrons
1	5.00E-07	5.70E-10
2	7.93E-07	5.83E-10
3	8.98E-07	2.23E-09
4	7.99E-07	5.77E-10
5	5.09E-07	4.13E-10

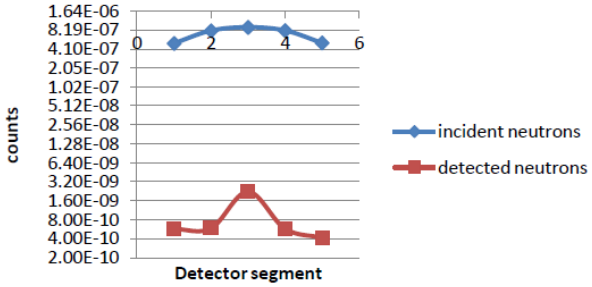

Fig. 19. Scenario F: 5 cm between collimator and detector.

Fig. 20 and 21 summarize the profile of the incident and detected beam in the six scenarios.

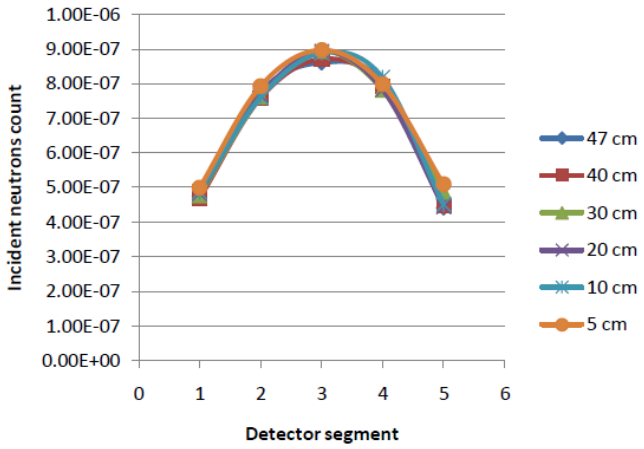

Fig. 20. Profile of the incident beam in the six scenarios.

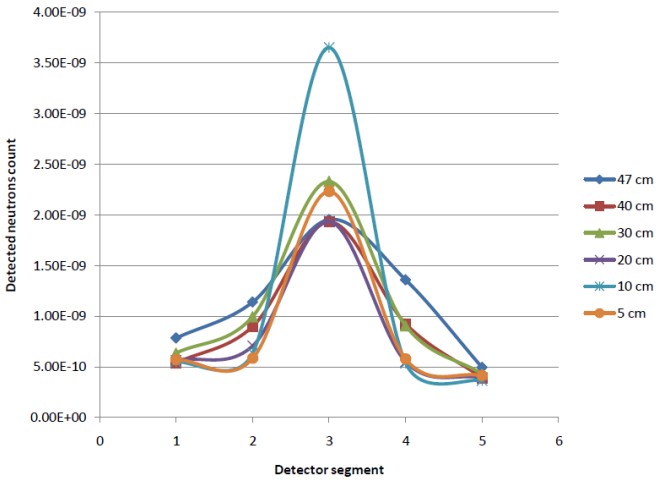

Fig. 21. Profile of the detected beam in the six scenarios.

V. Conclusion

Fig. 20 and 21 that the detected neutrons most concentrated in the central segment of detector which is placed in front of the collimated beam. The detected neutrons decrease as moving away from the collimator which can be seen as a 'bell shape' in the last plot. As the collimator is moved away from the detector, by moving the cadmium sheet, as the beam diverges. To avoid beam divergence, the slit in the cadmium sheet might be adjusted. The proposed design is with right angle edges.

References

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